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THE ATMOSPHERES OF THE ICE GIANTS, URANUS AND NEPTUNE

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I. Overview

In the 1990s it was realized that there are two types of giant planets in our solar system; gas giants and ice giants. Most familiar are the gas giants Jupiter and Saturn, which are composed mostly of hydrogen (more than 90% by mass). Their hydrogen envelopes are thought to extend all the way to their relatively small rock/ice cores, with molecular H_2 beginning a transition to ionized, metallic hydrogen at mega-bar pressures (Guillot 2005; Lissauer and Stevenson 2007). While Uranus and Neptune also possess hydrogen envelopes, they are much smaller, accounting for less than 20% of the planet's masses and never making the transition to metallic hydrogen (Guillot 2005). The bulk composition of these planets is dominated by heavier elements. Based on cosmic abundances, oxygen, carbon, nitrogen, and sulfur are the likely candidates. Since these species are thought to have been incorporated into the proto-planets primarily as ices—either as solids themselves or as gas trapped in water-ice clathrates (Hersant et al. 2004)—the term "ice giants" has been adopted. Today, however, there is probably very little ice in Uranus and Neptune, a supercritical fluid being the preferred phase of H_2O at depth. In 2004, the first of many ice giant candidates was reported around another star (Butler et al. 2004), indicating that they are common in our galaxy.

Both the gas and ice giants support complex and long-lived weather features in their gaseous outer layers. Strong zonal winds, polar vortices, and large scale circulation patterns have been observed, though there is not yet a satisfying model for why these features exist. All the giant planet atmospheres also support a rich variety of chemical pathways and contain disequilibrium species, driven in part by UV radiation from above and perhaps by mixing from as deep as the core. In spite of these similarities, the ice giants are fundamentally different from their gaseous cousins, and offer unique insights into not only atmospheric physics, but also the formation and evolution of all planets. In regards to atmospheric physics, Uranus and Neptune are laboratories for studying how stellar radiation from above and internal heating from below influence atmospheric structure. They inhabit much different regions of the parameter space than the gas giants: sunlight is weaker at the ice giants, Neptune has the largest ratio of emitted internal heat to absorbed sunlight (approximately 2.6, compared to Saturn's next highest value of 1.8), while Uranus is emitting the least internal heat (by mass, about ten times less than Neptune, Pearl et al. 1990). Some have speculated that Uranus' low emission is related to its extreme 98° obliquity, which causes seasonal forcings much different than any other giant planet in our solar system.

Dynamically, the ice giants also show striking differences from gas giants which, if understood, can teach us about basic processes in planetary atmospheres. On Neptune, for example, the largest visible features (the so-called "Great Dark Spots") form and dissipate on a time scale of years (Hammel et al. 1995), while the comparably sized Great Red Spot on Jupiter persists for centuries. The compositions of the ice giant's atmospheres is also much different than the gas giant's. This reflects their different bulk compositions, but also condensation and chemical reactions that are not present on Jupiter and Saturn (Weidenschilling and Lewis 1973; Gulkis et al. 1978; Atreya and Romani 1985). Understanding how these unique aspects of the ice giants are expressed in their atmospheres will help us understand how all giant atmospheres function. In particular, these insights may help us understand the extrasolar giant planets discovered that are close to their stars and have extreme stellar forcing (the so-called hot-Jupiters) or the ones whose mass and radius place them between the gas giants and terrestrial planets of our solar system (Butler et al. 2004). Understanding Uranus' and Neptune's atmospheres is also important because the gas envelope is the filter through which we see the interior. Trace species in these atmospheres offer important (and in some cases our only) clues about the bulk composition of the planets and the evolution of their cores. Even the interpretation of gravity-field measurements is influenced by atmospheric phenomena, such as the zonal winds (Anderson and Schubert 2007; Militzer et al. 2008).

The remainder of this White Paper will outline the most important science questions to be addressed by studies of the atmospheres of the ice giants. We conclude that a New Frontiers mission to an ice giant should be made a priority for the 2013 to 2023 time-frame. We will not attempt to prioritize Uranus over Neptune in this regard as either one can serve as the archetype for ice giant atmospheric science, and each has features not seen on the other which are worthy of study.

II. Top-Level Atmospheric Science Questions

In this section we will outline some of the important science to be done on the atmospheres of ice giants, and measurement strategies for addressing them. We have organized them around four top-level questions. The order in which they are presented is not indicative of priority.

Additional information, including detailed measurement objectives, are available at
http://www.atm.ox.ac.uk/user/fletcher/Site/Outer_Planet_Science_Goals.html
(Fletcher 2009).

Question 1: What is the composition of the atmosphere?
Why this is important: This is a fundamental property of an atmosphere, and it influences the temperature (wet vs. dry adiabats), stability (density) and cloud structure (what and where species condense). Condensable or disequilibrium species can also be used as tracers of atmospheric motion. For example, rising air parcels cool and become depleted in condensable such as H_2O and CH_4. In regions of subsidence, those air parcels warm but remain depleted. This has allowed IR and microwave remote sensing to infer much about the planetary-scale circulation of the planets (Hofstadter and Butler 2003; Karkoschka 2008). The composition can also be used to infer things about the formation and evolution of the planet: the relative abundances of species and their oxidation states help constrain the bulk abundances in the planet (Atreya et al. 2003; Hersant et al. 2004), and can be indicative of the rate of vertical mixing in the atmosphere and whether or not core erosion is taking place (where ice and rock from the core chemically react or physically mix with the overlying atmosphere).
Measurement approaches: It is important to measure composition as a function of latitude, altitude, and time. Species to measure include the noble gases, volatiles (such as NH_3, H_2S, and H_2O) the hydrogen ortho-para ratio, CO and other disequilibrium species, as well as isotopic ratios. A combination of in situ probes and remote sensing (both

ground- and space-based) is the best approach. Probes provide the most accurate data on all species and are the only way of measuring most of the noble gases, but probes have limited spatial and temporal coverage. Remote sensing, while less precise, provides the broad spatial and temporal coverage. In particular, high spatial- and spectral-resolution IR and submillimeter measurements are needed to determine smaller-scale composition, circulation, and temperature patterns in the upper troposphere and stratosphere, while high spatial resolution radio observations at wavelengths from 1 to 100 cm are needed to probe the deep troposphere (pressures ≥100 bar). Measurements must be made on two time-scales. Sampling on a scale of hours to a few days is needed to monitor weather patterns, while observations every few years over decadal time-scales are needed to track seasonal patterns (see Question 4).

Question 2: What is the nature of convection and circulation on the planets and how does it couple to the temperature field?
Why this is important: The three-dimensional, planetary-scale circulation pattern, as well as smaller-scale storms and convection, are the primary ways of moving energy (both kinetic and heat) and mass in the atmosphere, and are important for understanding planetary evolution. These processes couple different vertical regions of the atmosphere, and must be understood if we are to infer deeper atmospheric properties from observations of the upper layers. It is not known how the energy inputs to the atmosphere—solar insolation from above and the remnant heat-of-formation from below—interact to create the planetary-scale patterns seen on both gas and ice giants. Studying both types of planets to sample a range of obliquities, insolation values, and internal heat flow values is needed to untangle the role of each forcing mechanism. It is not only the planetary-scale features, however, which must be studied. The smallest-scale features are thought to maintain larger, longer-lived storms and the zonal flow as well, although the exact mechanism is not clear. The final goal is to be able to explain how the energy inputs to the atmosphere, combined with its composition, create the wealth of features seen on both ice and gas giants (the zonal flow, convective plumes, polar vortices, cloud bands) and the differences among them (why does Jupiter seem to be the only giant planet lacking an IR polar hot-spot? Why does Uranus emit ten times less internal heat than Neptune?)
Measurement approaches: High spatial resolution visible and IR imaging can locate and track cloud features to determine small-scale motions (5 micron imaging at Saturn by the Cassini spacecraft has been particularly illuminating in this regard). High spectral resolution IR and microwave imaging can map out the distribution of species (such as CO or CH_4) to infer the large-scale circulation of the upper atmosphere. Both spectral and broad-band continuum imaging at IR wavelengths can determine the temperature field of the upper atmosphere, while continuum radio imaging can probe the deep troposphere (pressures of tens to perhaps hundreds of bars) and map out the distribution of trace species there to infer circulation patterns at depth. Precise measurements of visible albedo and thermal emission at a range of solar phase angles and incidence angles (only possible from a spacecraft) will constrain the energy balance of the atmosphere and may shed light on transport mechanisms.

Question 3: What is the nature of clouds and hazes in the atmosphere?

Why this is important: Clouds and aerosols are related to atmospheric composition, chemistry, motion, and temperature, but we do not know the physical processes that control the interactions among these fields. For example, clouds on both Uranus and Neptune appear predominantly at certain latitudes, but we do not know why. Also, their vertical location and extent is being debated (for example, see the DPS abstracts Irwin et al. 2007, Karkoschka 2007, and Sromovsky and Fry 2007) but do not seem to match simple equilibrium chemistry models.
Measurement approaches: High spatial- and frequency-resolution imaging at visible and IR wavelengths constrains the location and properties of aerosols. Thermal IR imaging can also constrain the simultaneous temperature field. Continuum radio imaging at multiple wavelengths can constrain the vertical distribution of species such as water in the deep troposphere, which can be used as a proxy for cloud locations at depth. Atmospheric probes provide the most accurate information on temperature, composition, and aerosol abundances in a localized region, but require near-simultaneous remote sensing measurements to place them in the planetary context.

Question 4: What kinds of change occur on the ice giants and how are they driven?
Why this is important: Change in this context means weather and seasons; how do temperature, composition, convection, and large-scale circulation patterns vary over daily and seasonal time-scales? Observations at any one epoch cannot be interpreted properly if this variability is not understood. Understanding how changes are driven on ice giants as opposed to terrestrial or giant planets is also necessary for a fuller understanding of weather and climate processes and how they might act on extrasolar planets.
Measurement approaches: Observations of temperature, clouds, and atmospheric composition as described under Questions 1-3 of this section must be made on two time scales. First, there must be periods of frequent observations over the course of a few days or weeks to study weather phenomena (Hammel et al. 2005). Second, observations must be repeated every 2 to 5 years for many decades to track seasonal variability, since each season lasts 21 years on Uranus and 41 on Neptune (Sromovsky et al. 2003; Klein and Hofstadter 2006; Kramer et al. 2008).

III. Ground-Based Research and Research Facilities

Flight missions are required to address many of the key questions presented in Section II, but there are three main areas where ground-based work is helpful. First, ground-based astronomy has an important role to play. Optical and IR telescopes with diameters of 10 meters or more and large arrays of radio telescopes are crucial for tracking seasonal changes over many years and for providing information on large- to medium-scale atmospheric features. Space-based telescopes can also play these roles, and it is important for future generations of such telescopes, starting with the James Webb Telescope, to maintain capabilities for planetary observations.

A second area of useful research is in laboratory and computer studies. Interpretation of remote sensing measurements is often limited by a lack of knowledge of the optical, thermal, and chemical properties of various species believed present in ice giants, particularly at the extreme limits of temperature and pressure. For example, little is known about the microwave opacity of water or ammonia at pressures of hundreds of bars and temperatures of hundreds of Kelvin. Nor is the infrared opacity of H_2-He mixtures well understood under stratospheric conditions of the ice giants (pressures under 1 bar and temperatures near 60 K). Studies of fluid dynamics, both in physical labs and computer simulations, are needed to better understand what processes are important in rapidly rotating atmospheres.

A final area of supporting research is to carry out mission architecture studies for the ice giants. These are needed to determine what flight time, orbits, and spacecraft resources (mass and power) are available for science instruments, and what trade-offs among cost, reliability, and science return can be made.

IV. Technology Needs

The following are areas where technology development in flight hardware would benefit, or even enable, important ice-giant science.

- Low-power instrumentation. A recent JPL study has indicated that, for some ice-giant mission architectures, power and not mass is a limiting factor in the science capabilities of the spacecraft.
- Low-light, low-temperature solar arrays. As solar-array technology improves, it becomes feasible to fly spacecraft at and beyond Uranus without nuclear power.

V. Flight Mission Priorities

A New Frontiers class mission to an ice giant should be a priority for the latter part of the decade, with 2018 being a particularly efficient launch window. It is the only way to dramatically advance our understanding of this type of planet in the professional lifetime of currently working scientists. This mission would come at a crucial time for the study of extra-solar planets as well, where classifying planets based on no more than their mass, radius, and perhaps the presence of a few atmospheric species requires us to understand the full region of parameter space occupied by planets in our solar system (Sotin et al. 2007). Studies have indicated that Discovery-class missions are not feasible for Uranus and Neptune. A Flagship mission to an ice giant, such as the Neptune orbiter recommended by the first Decadal Survey, will likely come only after the Jupiter and Saturn Flagships recently chosen jointly by NASA and ESA, as well as a possible Flagship to a terrestrial planet. This would put the first data return from an ice giant Flagship more than 40 years into the future. Thus, New Frontiers (or the proposed "Small Flagship" class) appears to be the only practical way to address ice giant science with a flight mission in the next few decades. Programmatic balance also argues for a mission to an ice giant. They are the only class of object in our Solar System never to have a dedicated mission. In fact, all other major categories have a mission currently flying[1]. Only the ice giants are lacking this attention, which leaves key science questions in limbo.

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[1] For the terrestrial planets, Messenger (Mercury), Venus Express, and multiple orbiters and landers at Mars. The gas giants have Cassini, and Juno is under construction. Dwarf

In this White Paper, we have not chosen one ice giant over the other as the higher priority for study. This is because either Uranus or Neptune can serve as the archetypal ice giant atmosphere, advancing all the fundamental science we have described. Each planet also has intriguing features that the other does not. There are cross-disciplinary and programmatic considerations beyond the scope of this White Paper, however, which can be used when trying to prioritize between missions to Uranus and Neptune. We expect these will be discussed in separate White Papers that endorse specific mission ideas.

VI. Summary

We believe many important atmospheric science questions can only be addressed by studies of the ice giants Uranus and Neptune. These questions relate to fundamental atmospheric processes that help us understand the formation, evolution, and current structure of all planets, both in our solar system and beyond. In addition to supporting ground-based observations and laboratory work, we conclude that a New Frontiers mission to an ice giant should be made a priority for the 2013 to 2023 time-frame.

VII. References

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planets/Kuiper-belt objects will be visited by New Horizons (Pluto) and Dawn (Ceres). The asteroids are being visited by Dawn (Vesta) and Hayabusa. Finally, the study of comets is being advanced by the European's Rosetta mission, as well as NASA's extended missions Stardust/NExT and Deep Impact/EPOXI.

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